Particle Acceleration at Astrophysical Shocks Part II

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Outline of Lectures

- 1. Astrophysical source contexts;
- 2. Cosmic ray acceleration: Fermi's original idea;
- 3. Non-relativistic, test-particle shocks: canonical power-law generation;
- 4. Genres of theoretical approaches;
- 5. Non-linear effects in strong shocks: cosmic ray hydrodynamic modification;
- 6. Nuances: magnetic field amplification;
- 7. Relativistic shocks: non-canonical power-laws, acceleration times and thermalization vs. acceleration.

Red denotes today's topics

How do we develop Acceleration Theory?

- Analytic studies, usually as solutions of the diffusion/convection kinetic equation for particle transport, using some prescribed diffusion operator;
- This approach was adopted by most of the shock acceleration papers in the late 1970s on test particle theory;
- very useful for test particle applications; some applicability to non-linear problems (e.g. two fluid models [Drury, Voelk, Kirk, etc]) including spectral issues (Eichler, Ellison, Berezhko, Voelk, Malkov, Blasi, etc.);
- Must parametrically treat injection from thermal energies.
- More restricted use for relativistic shocks (Kirk, Blasi etc.), since diffusion approximation must be relaxed.

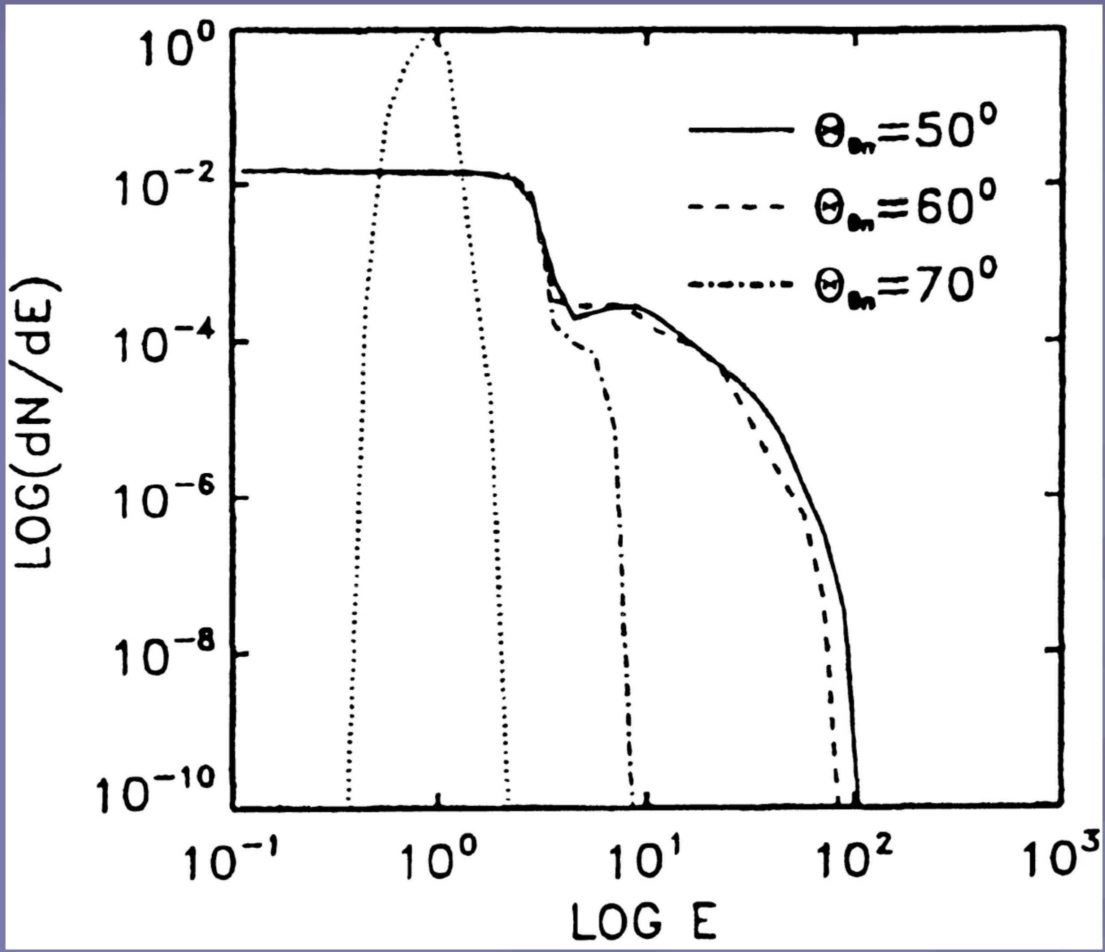
Monte Carlo Simulations

- Use a *kinetic description of convection and diffusion in MHD shocks* (Ellison, Jones, Baring + collaborators);
- Thermal ions and electrons are injected far upstream of shock;
- Particle diffusion is phenomenologically described via mean free path □ being some power of its gyroradius r_g: same prescription for both thermal and non-thermal particles;
- Simulations are fully relativistic, and not restricted to subluminal shocks => excellent for treating relativistic shocks;
- Ideal for use in non-linear problems where large dynamic (momentum + spatial) scales must be handled;
- Well-tested against heliospheric shock data.
- Magnetic turbulence can be incorporated (Ostrowski et al.), though plasma effects cannot be fully modeled.

Hybrid and Full Plasma Simulations

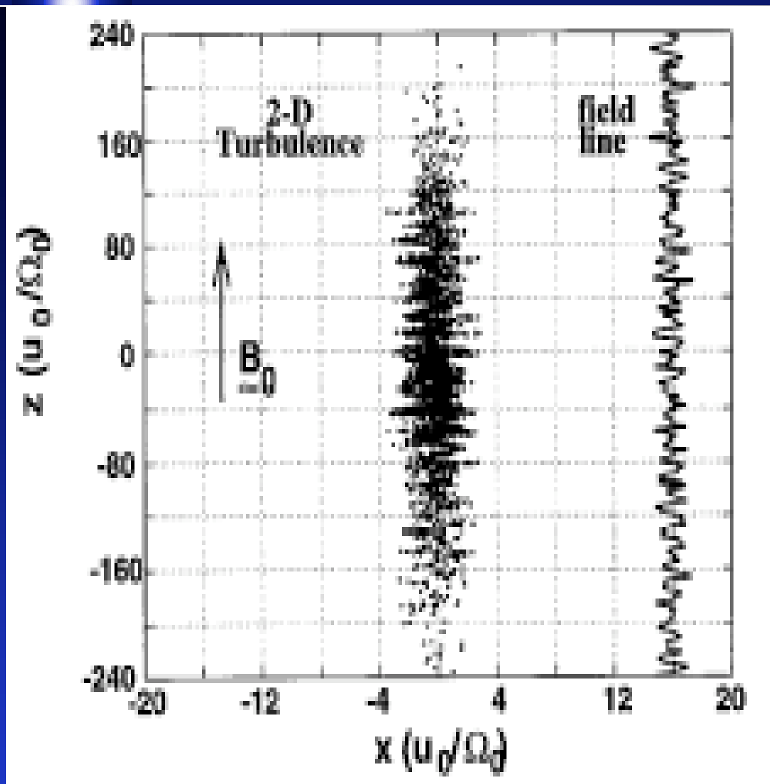
- Plasma simulations encapsulate important plasma physics, solving Maxwell's and the Newton-Lorentz equation in confined boxes;
- Hybrid simulations treat electrons as a background fluid, and so model ion acceleration;
- Particle-in-cell (PIC) codes treat full plasmas, but are often restricted to low e^- to p mass ratios;
- Ideal for exploring shock layer physics, but unable to model large scale issues such as shock modification;
- Such simulations have historically been performed in limited dimensions (CPU constraint), with potentially critical loss of physics.

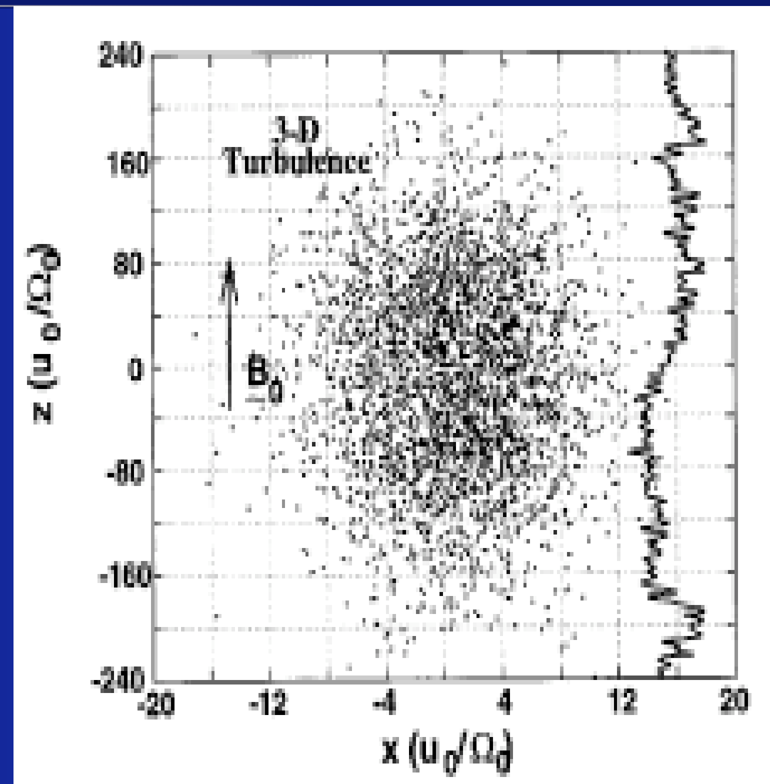
Difficulty with quasi-perpendicular shocks: hybrid plasma simulations



Kucharek & Scholer (1995)

Cross-field Diffusion Theorem

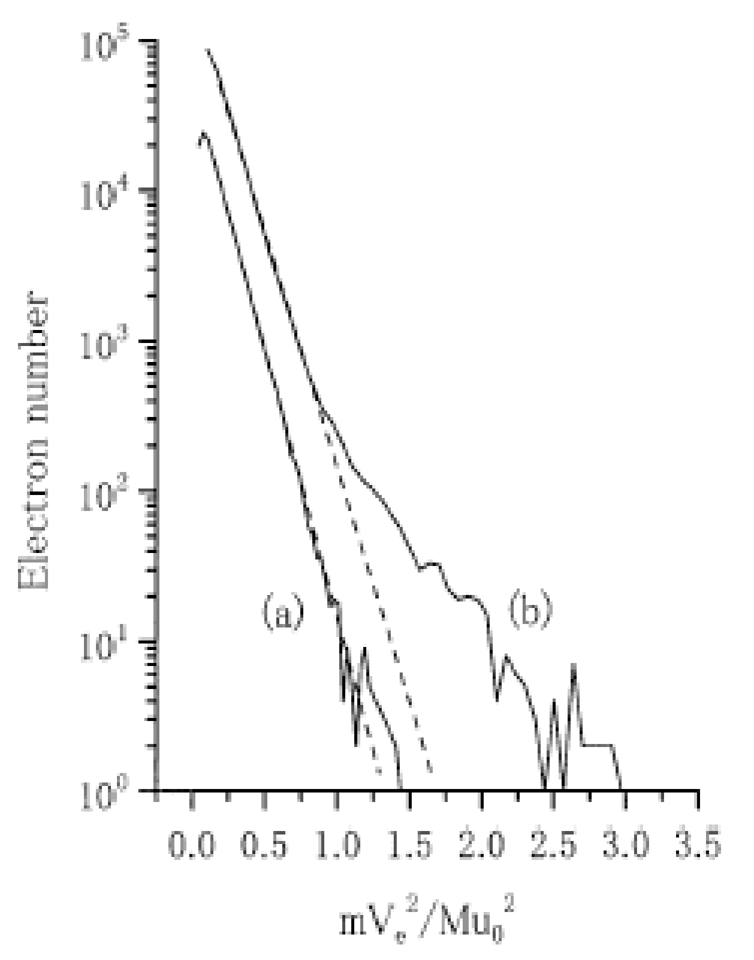




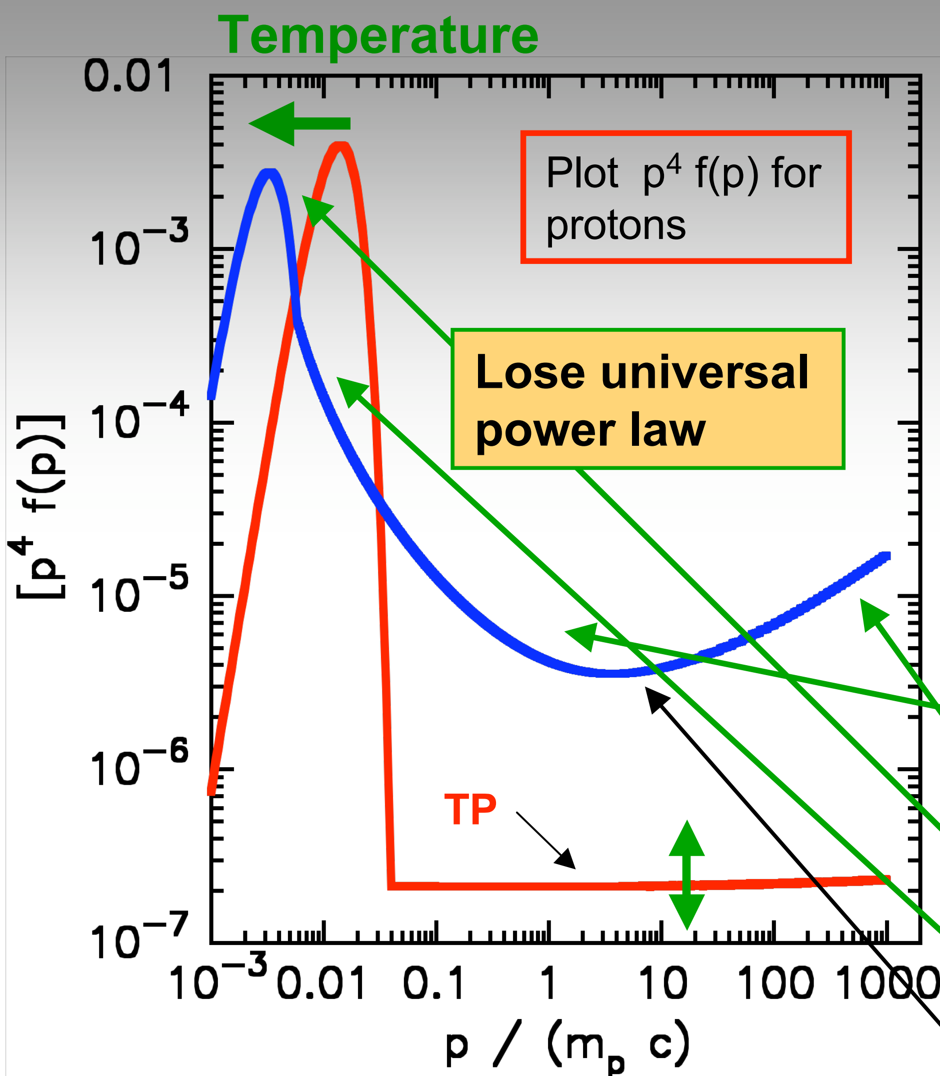
- Giacalone & Jokipii (1994): restricted dimensionality in plasma simulations inhibits cross-field diffusion (see also proof in Jones, Jokipii & Baring 1998).

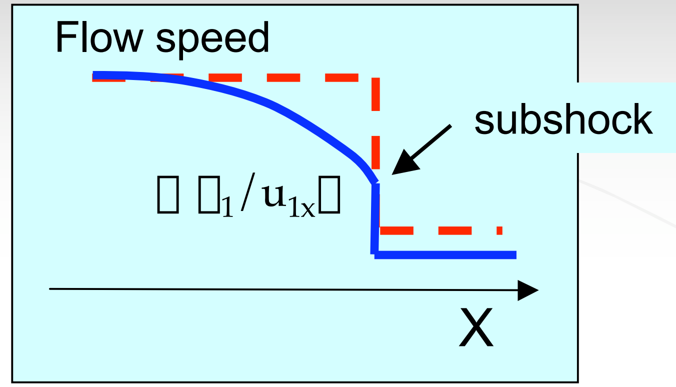
1D PIC (Particle-in-cell) Simulations

- Shimada & Hoshino (2000), electron-ion, Q-perp, non-rel. shocks;
- High $M_{A:}$ Two-stream electrostatic instability heats e^-;
- Plasma physics over-rides diffusion limitations in Q-perp shocks.



If acceleration is efficient, shock profile is smoothed by the upstream backpressure of CRs.





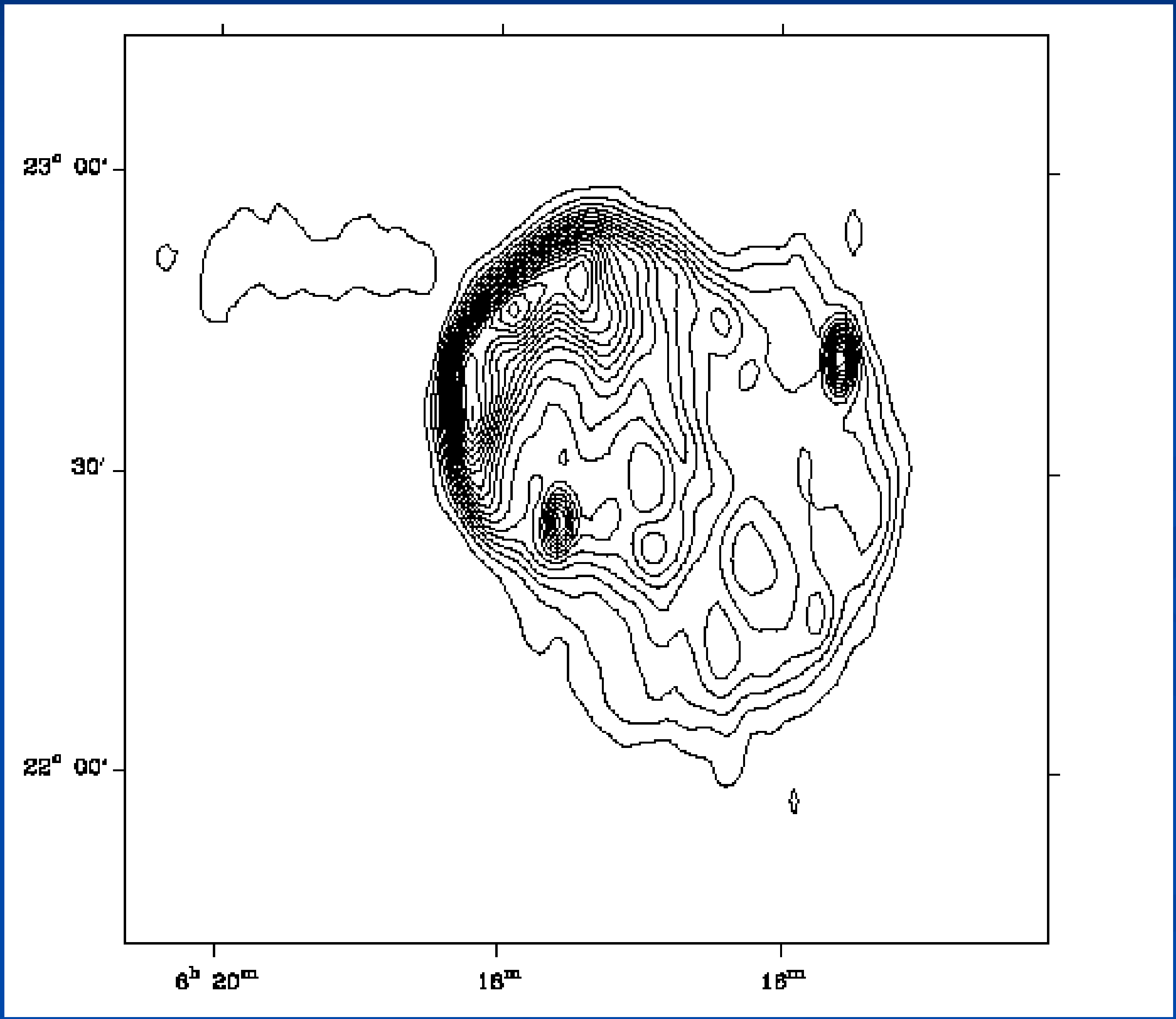
- **Concave spectrum**
- **Compression ratio, $r_{tot} > 4$**
- **Low shocked temp. $r_{sub} < 4$**
- **Nonthermal tail on electron & ion distributions**

Shown is analytic model of Blasi (2002)

In efficient acceleration <u>entire spectrum</u> must be described consistently;
connects photon emission across spectrum from radio to γ-rays.

Courtesy: Don Ellison

Supernova Remnants: Cosmic Habitats for Non-Linear Modification



IC443

Radio map, courtesy of Dave Green

Origin of Non-Linear Cosmic Ray Modification of Shocks

- The essence of nonlinear modification of shock hydrodynamics by accelerated cosmic rays is encapsulated in the energy flux Rankine-Hugoniot relation:

$$\frac{1}{2}\rho_1 u_1^3 + \frac{\gamma_{\rm eff}\, u_1 P_1}{\gamma_{\rm eff}-1} + \mathcal{E}_{\rm esc} \;=\; \frac{1}{2}\rho_2 u_2^3 + \frac{\gamma_{\rm eff}\, u_2 P_2}{\gamma_{\rm eff}-1} - \mathcal{E}_{\rm rad}$$

- Here $\mathcal{E}_{\rm rad}$ is the (positive) energy flux *lost to radiation*, predominantly downstream of the shock.
- Moreover, $\mathcal{E}_{\rm rad}$ is the energy flux contribution from *particle escape* (e.g. in spherical SNR shells) *upstream*.
- Both lead to a softer equation of state, i.e. a reduction in the effective adiabatic index, $\gamma_g \to \gamma_{\rm eff} < \gamma_g$, corresponding to a stronger shock $r \sim (\gamma_{\rm eff}+1)/(\gamma_{\rm eff}-1) > 4$. Also, r *increases further upstream of the shock* due to cumulative escape.

Non-Linear Spectral Concavity

- Due to cumulative escape upstream, the compression ratio monotonically increases further upstream of the shock: $dr/dx < 0$. Hence, since the particle distribution is given by

$$f(p) \propto p^{-\sigma} \; , \quad \sigma = \frac{r+2}{r-1} \; , \quad r = \frac{u_{1x}}{u_{2x}} \; ,$$

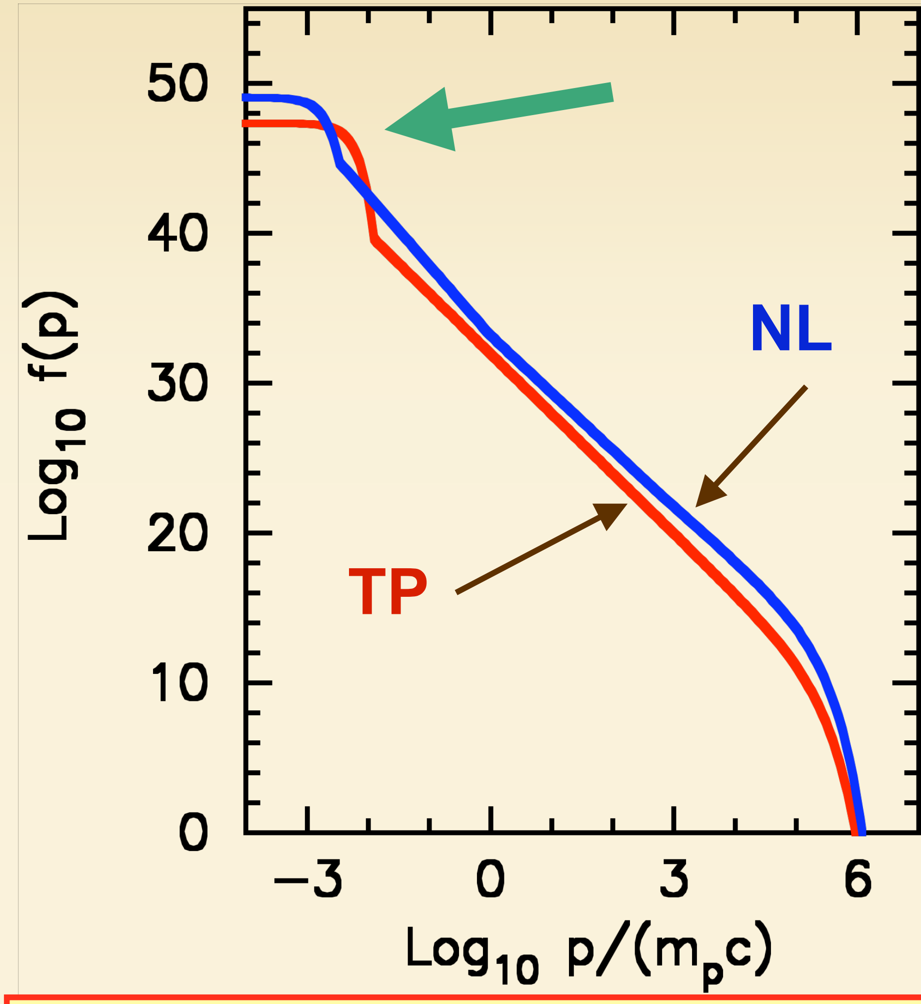
we have $\sigma = \sigma(x)$ with $d\sigma/d|x| < 0$.

- Diffusive scales upstream are coupled to particle momenta according to (for $\alpha > 0$ and $\alpha \sim 1$)

$$x \sim \frac{\kappa_1}{u_{1x}} \propto p^{\alpha} \quad \Rightarrow \quad \sigma \equiv \sigma(p) \quad \text{with} \quad \underline{\underline{\frac{d\sigma}{dp} < 0}} \; .$$

- **The spectrum gets flatter at higher momenta.**

Courtesy: Don Ellison



Without p^4 factor in plot, nonlinear effects much less noticeable → hard to see in cosmic ray observations.

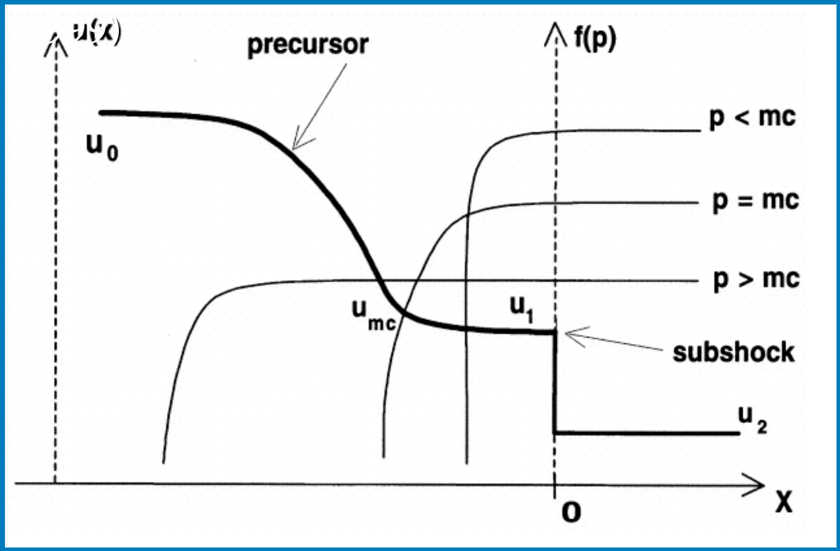
Most important point for X-ray observations: the more efficient the cosmic ray production, the lower the shocked temperature. This is a large effect!

Compression ratios, r_{tot} > 4 result from:

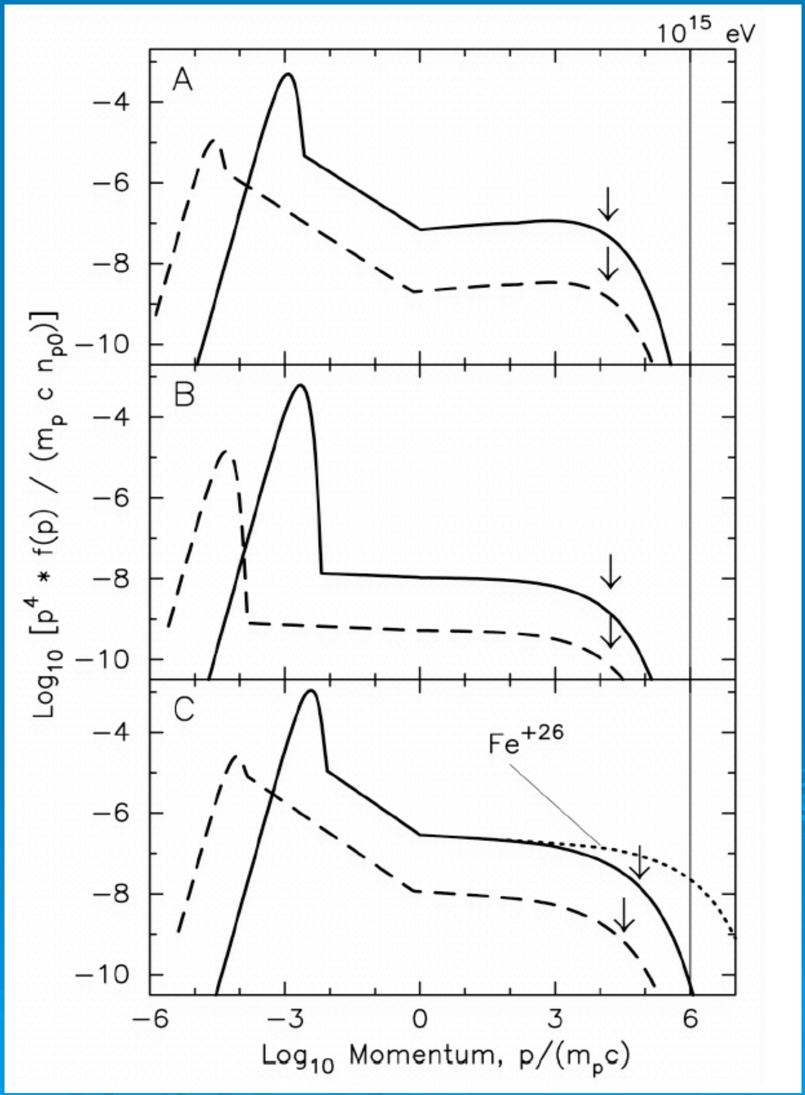
1. **contribution to pressure from relativistic particles (Gamma=4/3, r_{tot}→ 7); this changes for relativistic shocks;**
2. **particle escape (r_{tot}→ infinity) at Emax (c.f. radiative shocks).**

Non-Linear Shock Modification

Berezhko & Ellison



Ellison & Cassam-Chenaï (2005)



NL

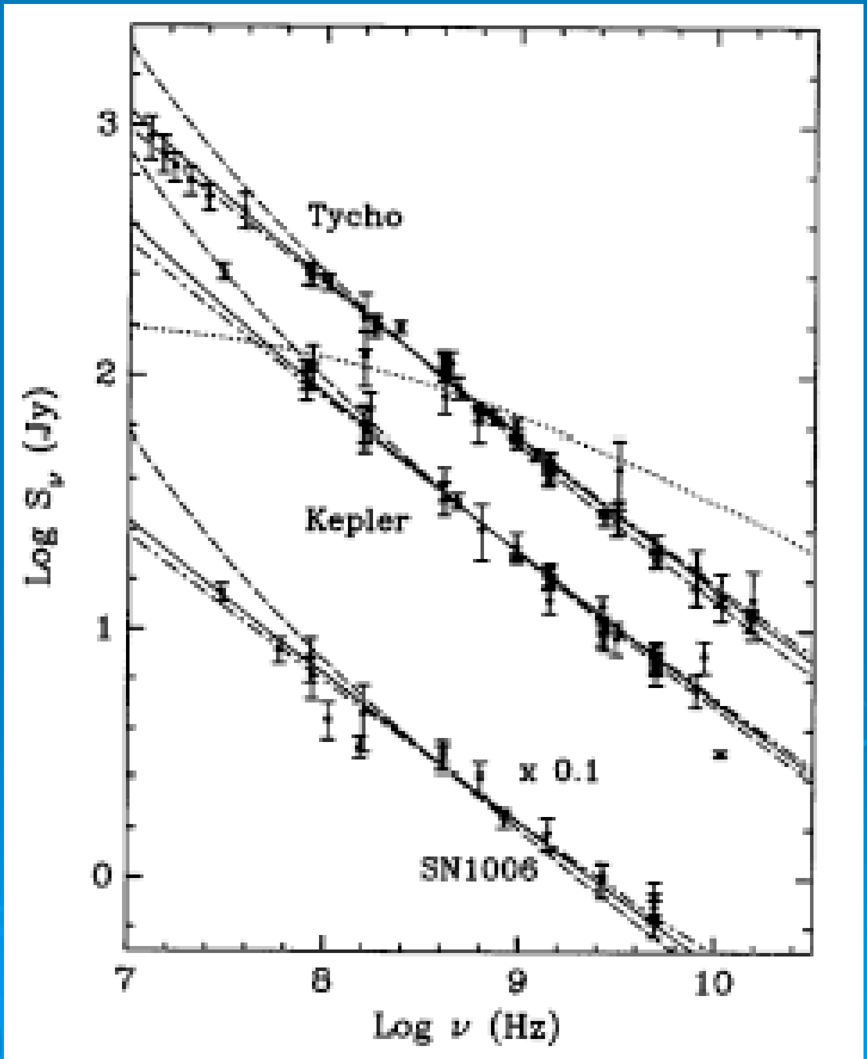
TP

Solid = protons, dashed = electrons

- Pressure supplied by energetic CRs slows upstream flow and reduces subshock compression ratio;
- => lower heating of ions and electrons, i.e. T_e drops below unmodified HD expectations.

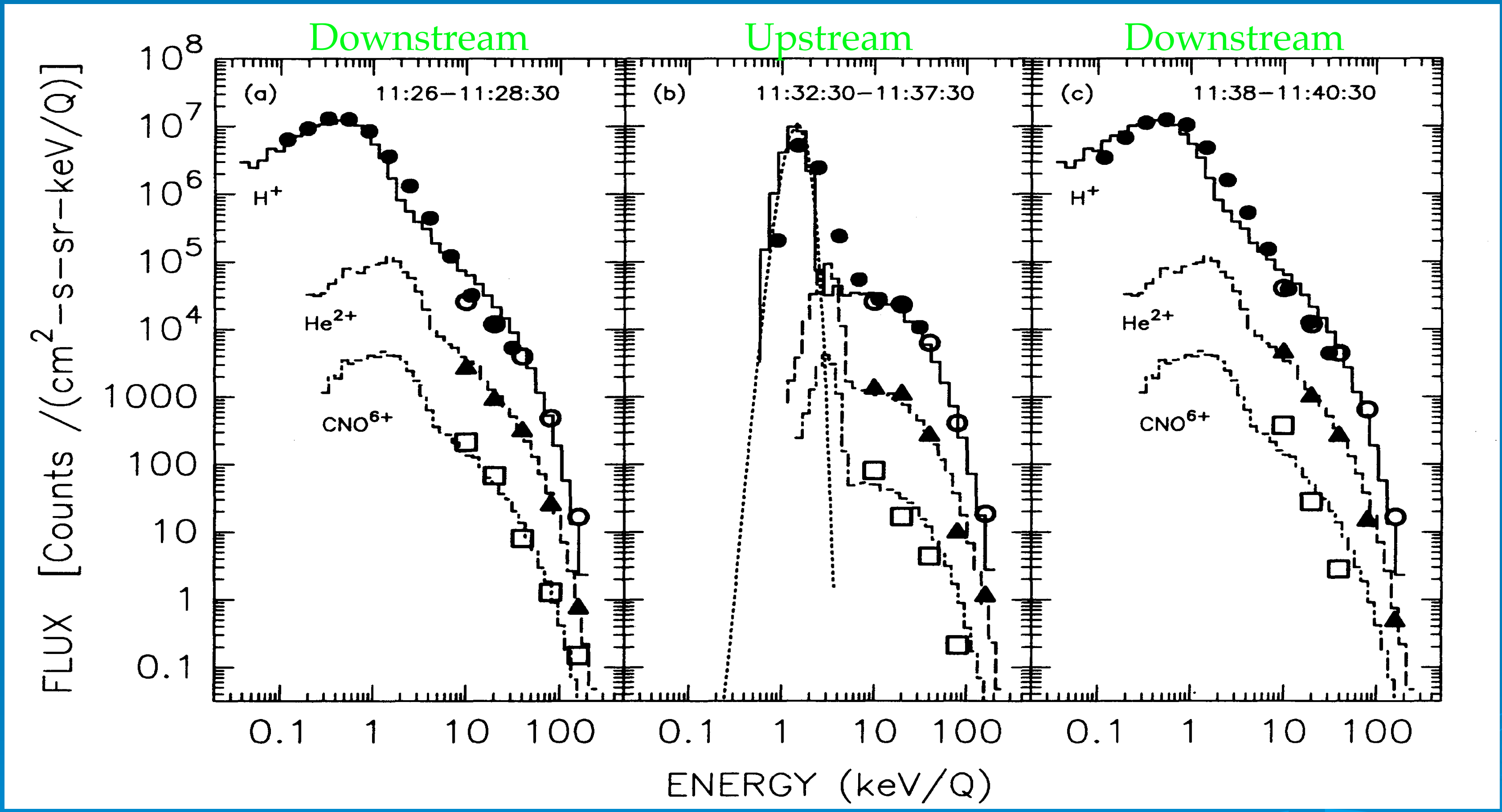
Marginal Evidence for Non-Linear Curvature in Radio SNRs

- NL effects not yet demonstrated unequivocally in SNRs (e.g. Reynolds & Ellison 1992, radio data compilation for Tycho + Kepler).
- Need broad-band spectra such as that to be provided by GLAST and TeV telescopes.



Ion Acceleration at Earth's Bow Shock

Ellison, Mobius & Paschmann (1990)



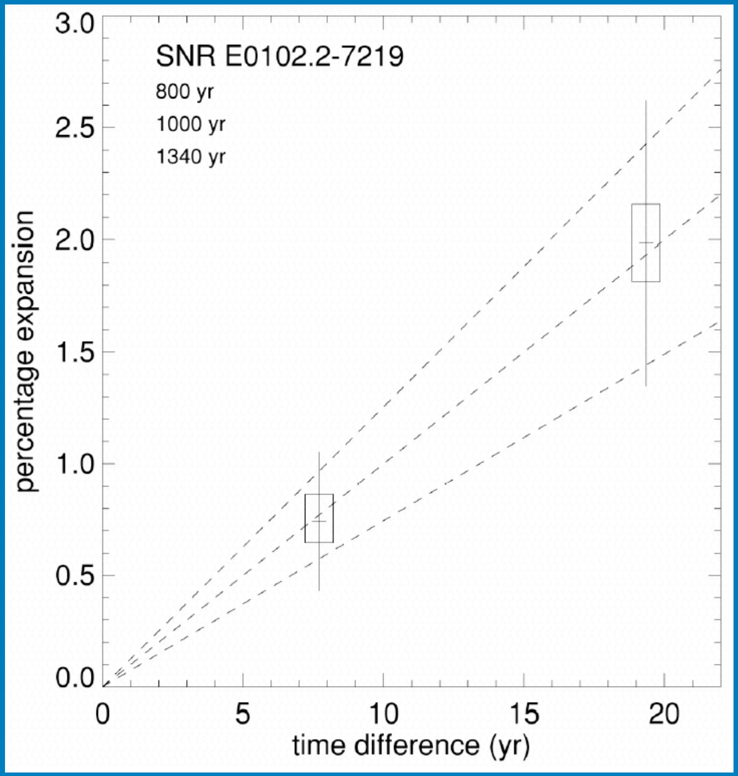
- AMPTE observations of diffuse ions at Q-parallel Earth bow shock H^+, He^{2+} and CNO^{6+} observed during time when solar wind magnetic field was nearly radial;
- Efficient acceleration (25%) in high MS shock; model fits work only for non-linear model that exhibits A/Q enhancements; Scholer, Trattner & Kucharek (1992) found similar results with hybrid PIC simulations.

A/Z Enhancement

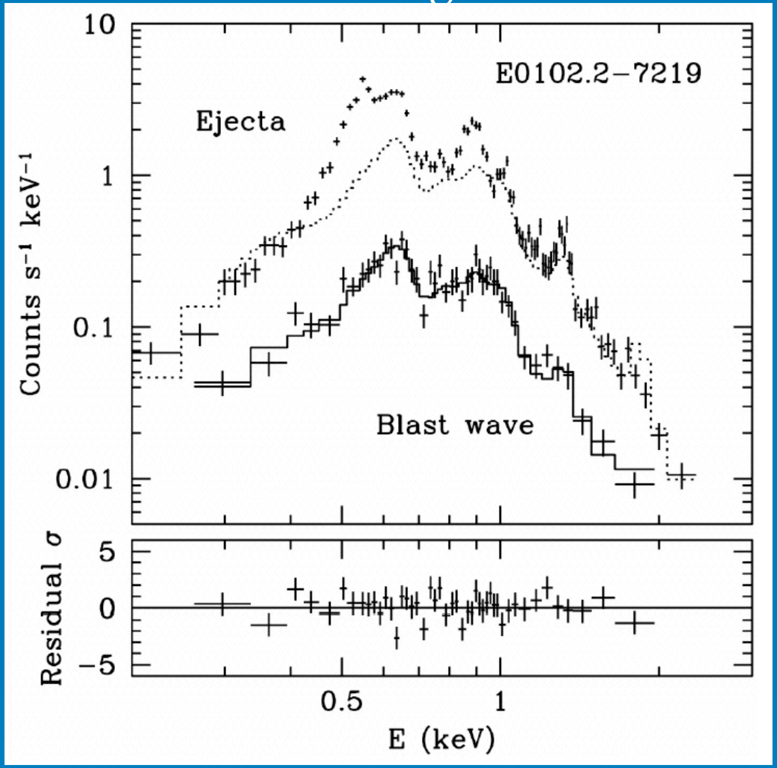
- The upstream spatial diffusion scale depends on the mass number A and charge Q=Ze of the ion,
- via the dependence of the mean free path □ ~ □ r_g A□m_pc/(ZeB). Since □ samples the modification spatial scale, heavy elements with high charge states (e.g. Fe^{26+}) are preferentially accelerated to higher energies, and with greater efficiency;
- Applications include: the Earth bow shock, anomalous cosmic ray production at the solar wind termination shock (Cummings & Stone 1995; Ellison et al. 1999);
- Dust grain model for seeds of galactic cosmic ray generation (Meyer, Drury & Ellison 1997).

Electron Temperatures in the Shock Layer

ROSAT/Chandra

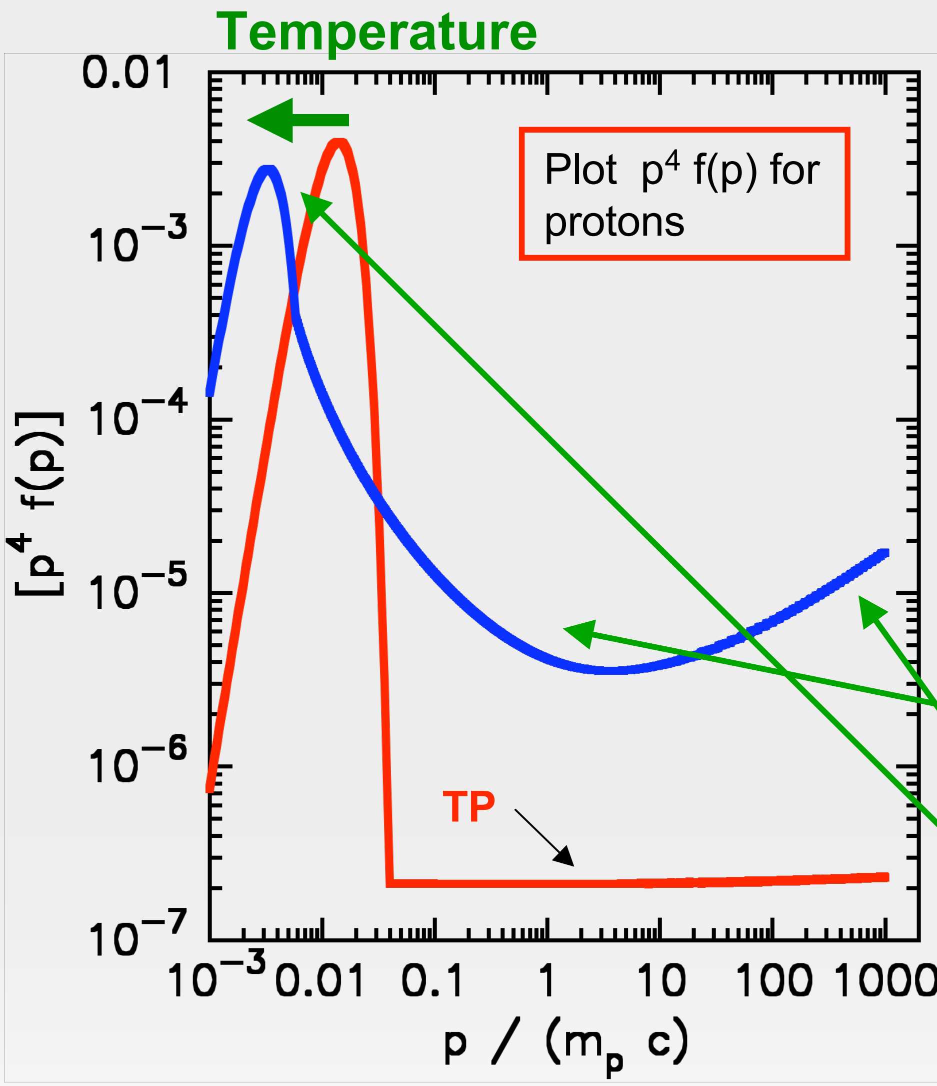


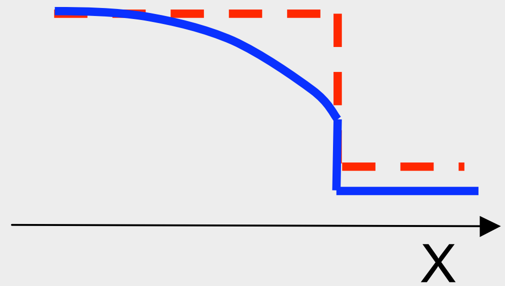
Hughes et al. 2000



Chandra

- Hughes et al. (2000; E0102.2) & Decourchelle et al. (2000; Kepler) observed that NE ionization fits to X-ray spectra (O, Ne, Fe, Mg lines) yielded T_e below hydrodynamic (HD) expectations: $3kT_e/2 < m_e(3u_1/4)^2/2$;
- Ram pressure HD quantities deduced from proper motions: usually radio, sometimes X-ray (left panel: ROSAT/Chandra);
- Concluded that low post-shock T_e and high line brightness could be produced by *non-linear* acceleration models.





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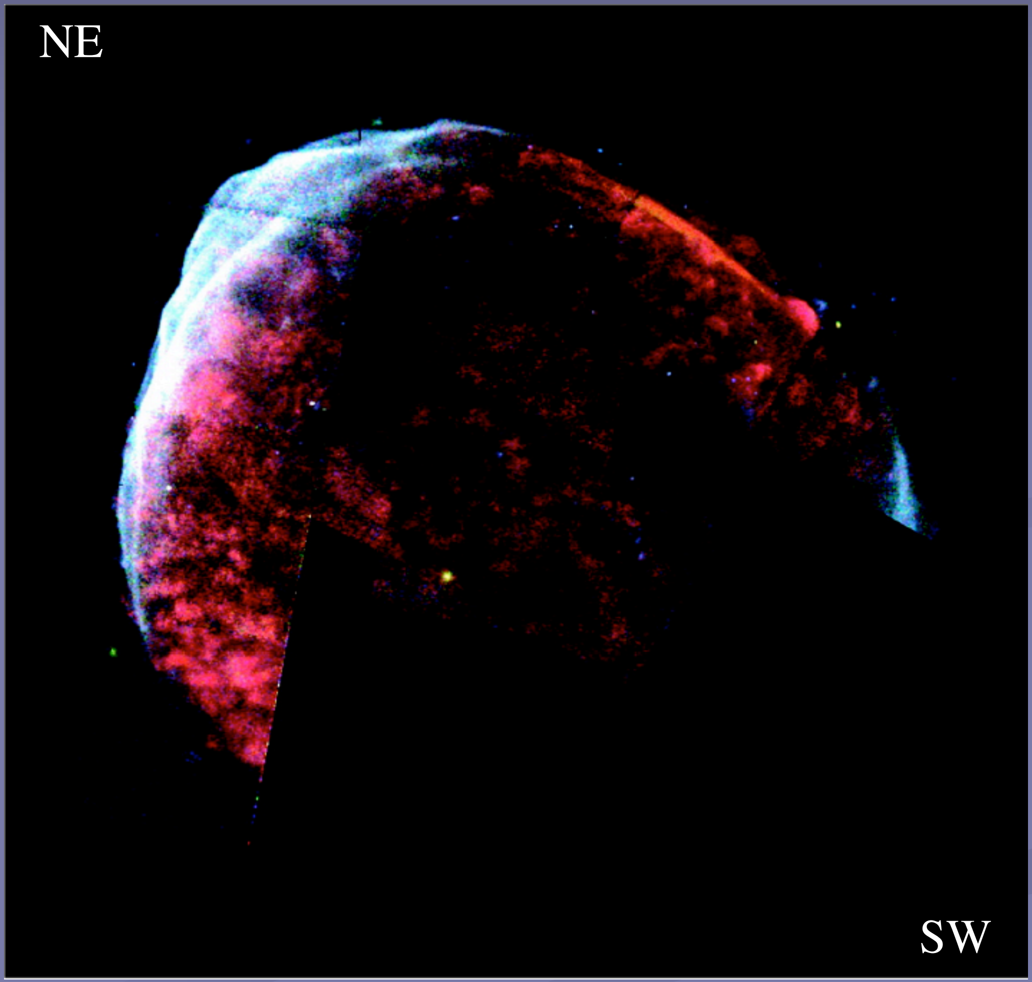
Courtesy: Don Ellison

Inferences of SNR B Fields using CHANDRA

- Spatially-resolved line and continuum spectroscopy by CHANDRA X-ray Observatory permits probes of **B** field amplification in SNRs;
- Case study: SN1006 (Long et al. 2003), a clean system, i.e. early Sedov-phase (deduced from radio proper motions), simple environment (high latitude source), with well-defined shell;
- Spatial mapping of thermal (i.e. line) and non-thermal synchrotron emission details magnetic field contrast across quasi-perpendicular shock.
- Southwest rim (not shown) similar to NE image.
- Thermal interior (red) and non-thermal shell (blue).

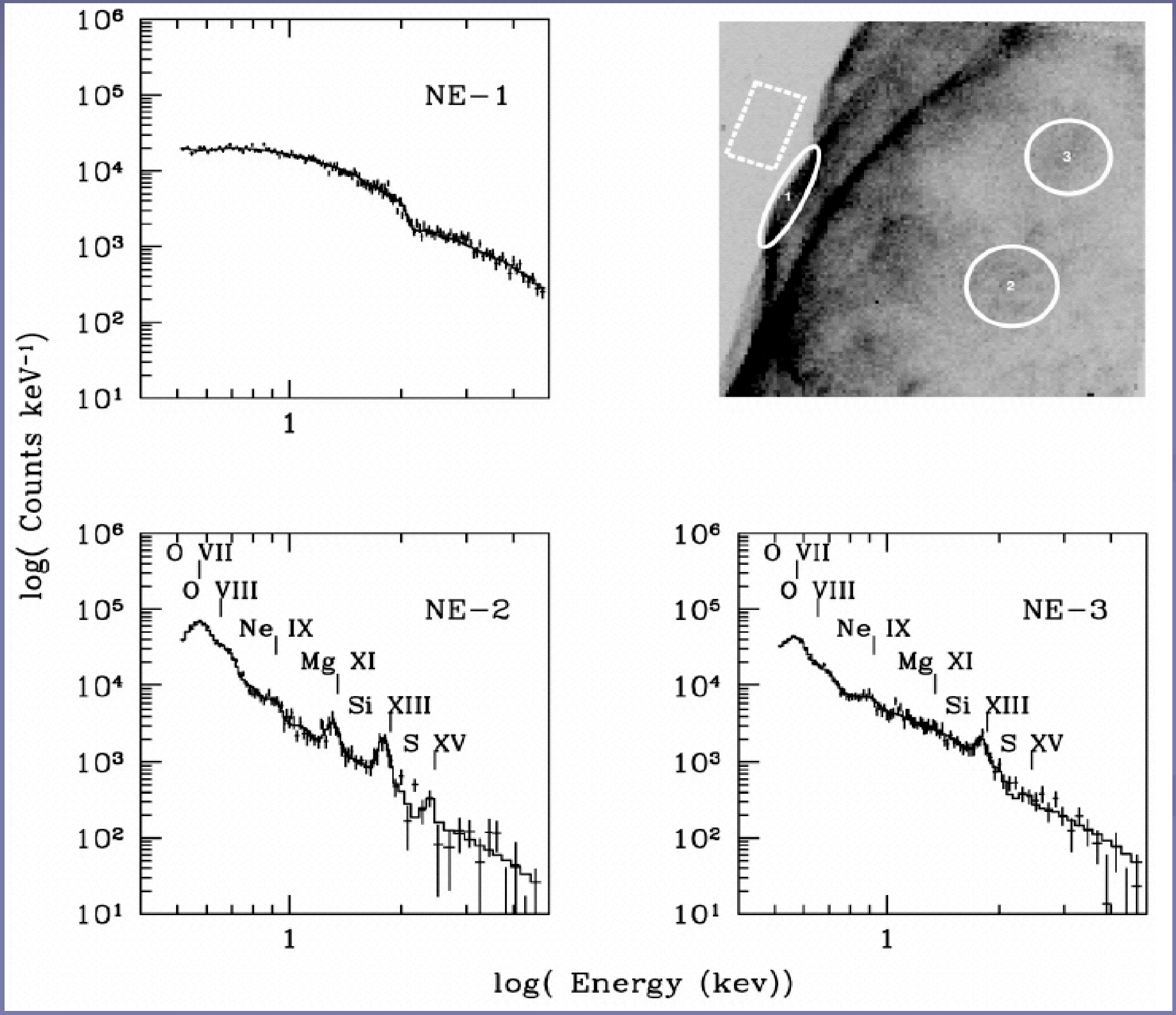
SN1006



Red: 0.5-0.8 keV;
Green: 0.8-1.2 keV;
Blue: 1.2-2.0 keV.

Spatially-Resolved Spectroscopy with CHANDRA

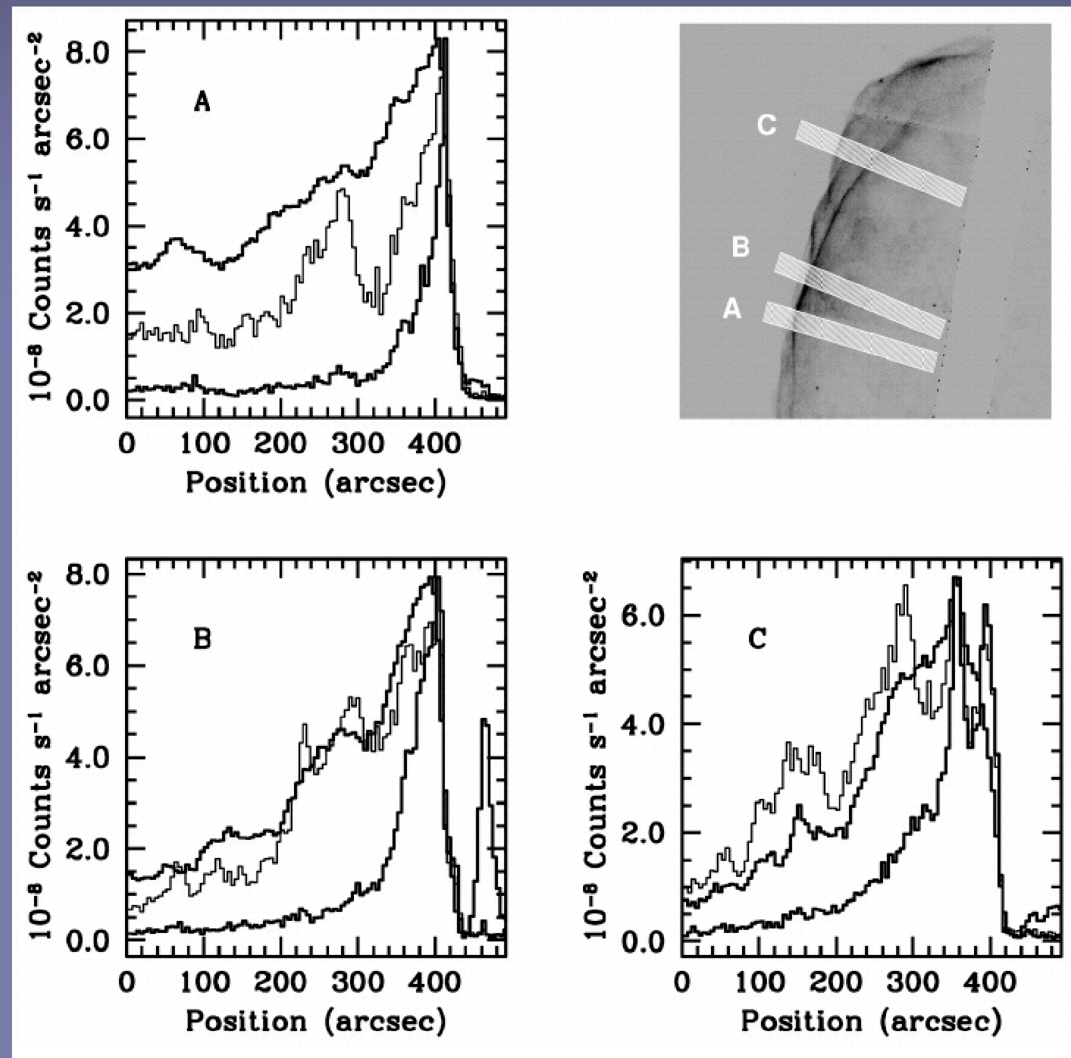
- Clear spectral evolution from non-thermal to thermal away from rim;
- Without spatial resolution, two components were confused, with the non-thermal rim dominating.



Spatial Brightness Profiles in SN1006

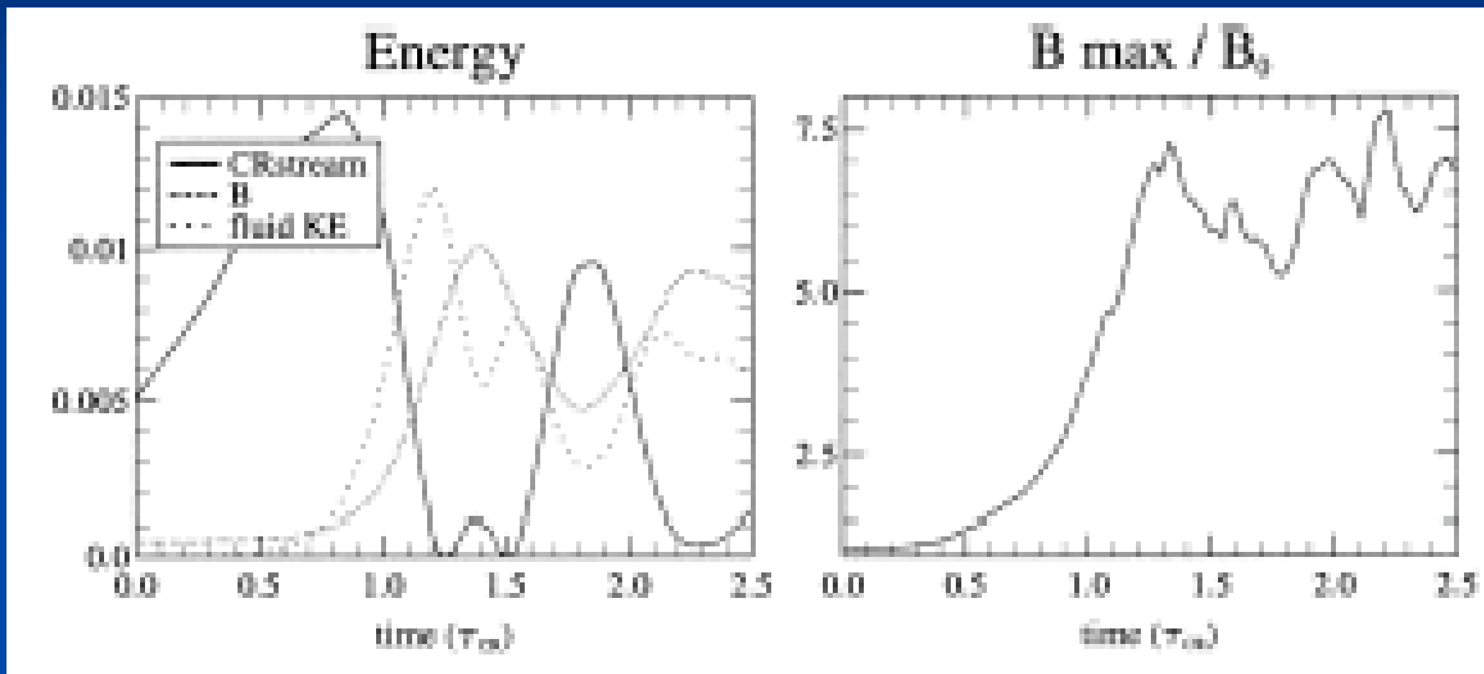
Long et al. 2003

- Surface brightness profiles are much broader for thermal X-rays and radio synchrotron than for non-thermal X-rays;
- Narrowness of profiles along scans argues for shocks $\perp$ to sky, i.e. no projectional smearing;
- Flux contrast ratio (< 1.5%) for upstream to downstream 1.2-2.0 keV suggests $B_d/B_u >> 4$, i.e. *greater than standard MHD compression in high M_S shocks* (Cas A offers similar picture: Vink & Laming 2003);
- Non-thermal X-ray width suggests a connection between cosmic rays and **B**-field amplification.



Thin black line: 0.5-0.8 keV; Black line: 1.2-2.0 keV; Grey line: 1.4 GHz radio.

Non-Linear Field Amplification by Cosmic Ray Streaming



- Lucek & Bell (2000) proposed that high energy cosmic rays (CRs) in strong shocks could amplify B when streaming upstream;
- Work done on Alfven turbulence scales as the CR pressure gradient: $dU_A/dt = v_A\, dP_{CR}/dx$;
- Field amplification should then scale as $(dB/B)^2 \sim M_A\, P_{CR}/$□$u^2$; works for high M_A strong shocks that generate large P_{CR}.

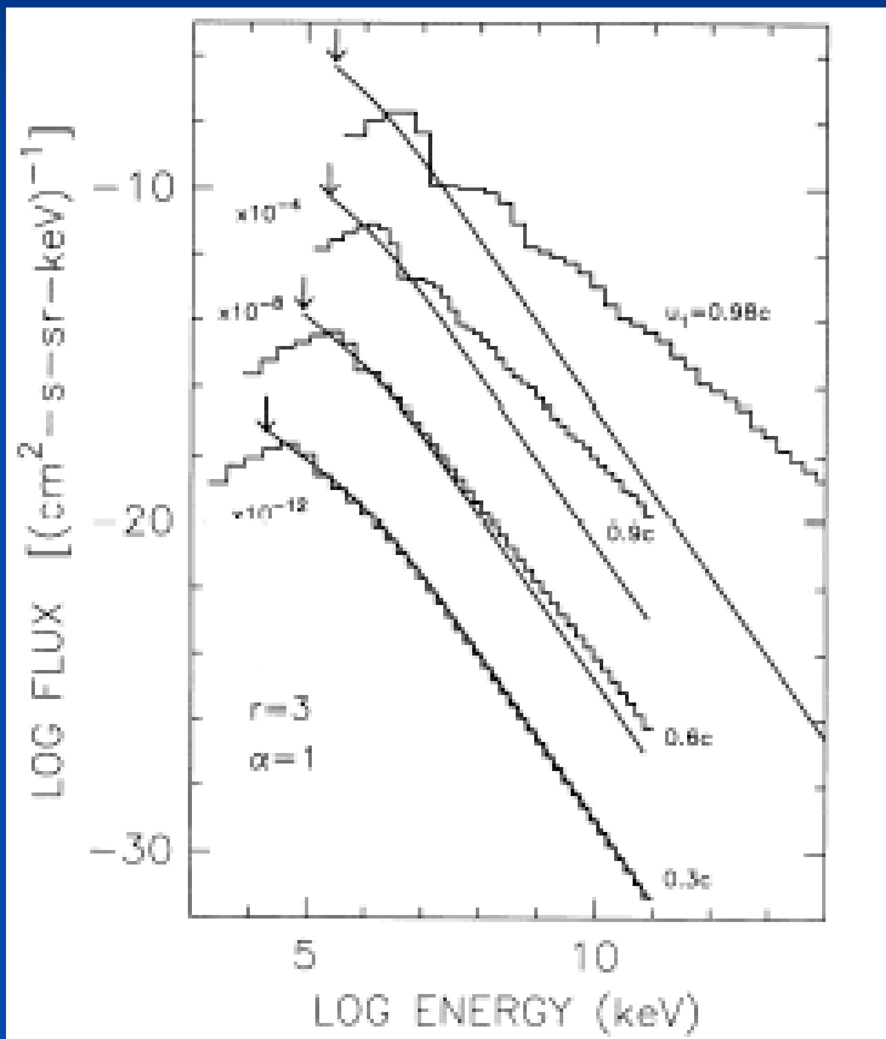
Electron Heating and Injection

- Electrons are injected into acceleration processes in astrophysical shocks: mechanism for this is still unkown.
- Electrons do not resonantly interact with Alfven waves until they are relativistic for typical SNR environmental parameters. Whistler waves buy some parameter space, down to kT_e~10-30 keV (Levinson 1992);
  - Role of whistlers is yet to be thoroughly explored in simulations;
- But some extra heating or pre-acceleration in SNR shocks is needed to seed diffusive or other acceleration at higher energies;
- Electrostatic potentials or instabilities play a role (e.g. Shimada & Hoshino 2000; Baring & Summerlin 2006).

Distinguishing Properties of Relativistic Shocks

- For small angle scattering, ultra-relativistic, parallel shocks have a power-law index of 2.23 (Kirk et al. 2000);
- Result obtained from solution of diffusion/convection equation and also Monte Carlo simulations (Bednarz & Ostrowski 1996; Baring 1999; Ellison & Double 2004);
- Power-law index is **not universal**: scattering angles larger than Lorentz cone flatten distribution;
- Large angle scattering yields kinematic spectral structure;
- Spectral index is strongly *increasing* function of field obliquity.

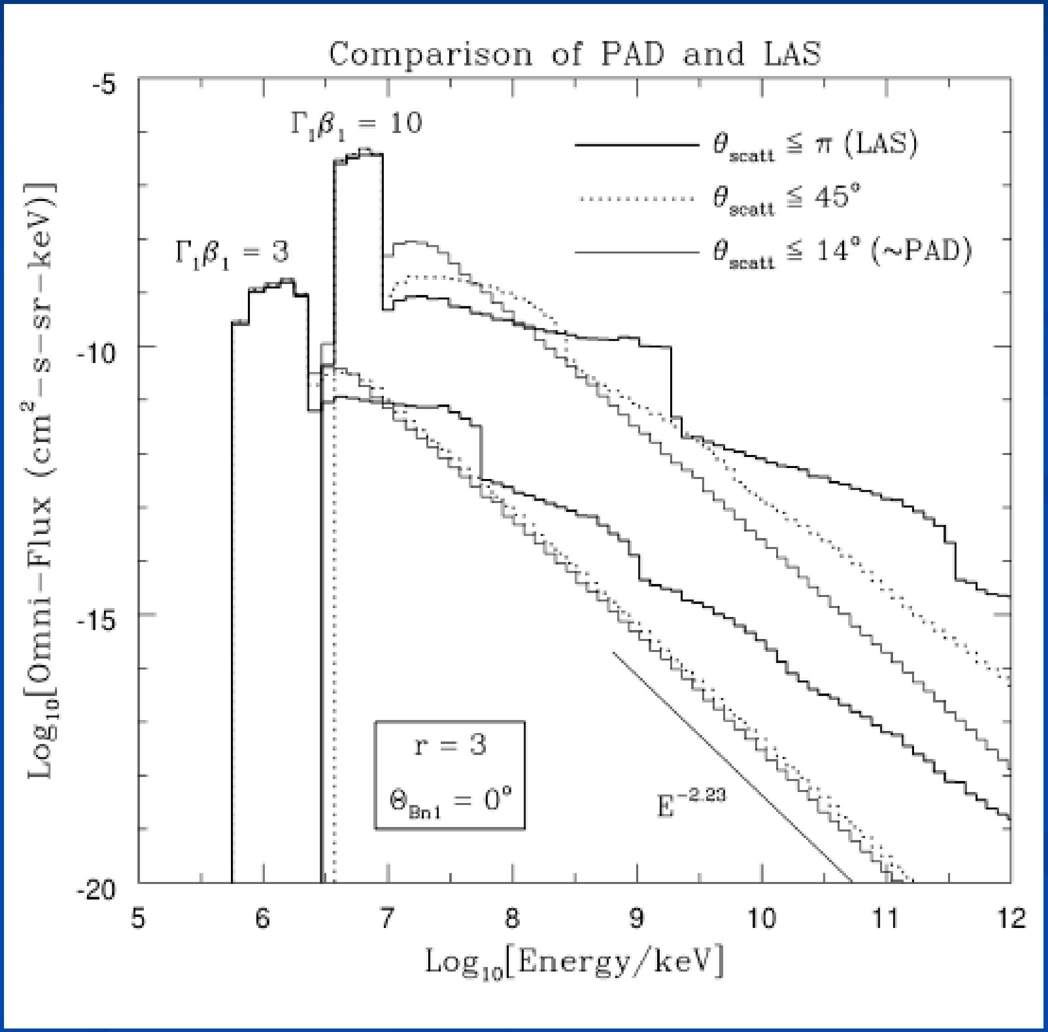
Ellison, Jones & Reynolds (1990): Large Angle Scattering



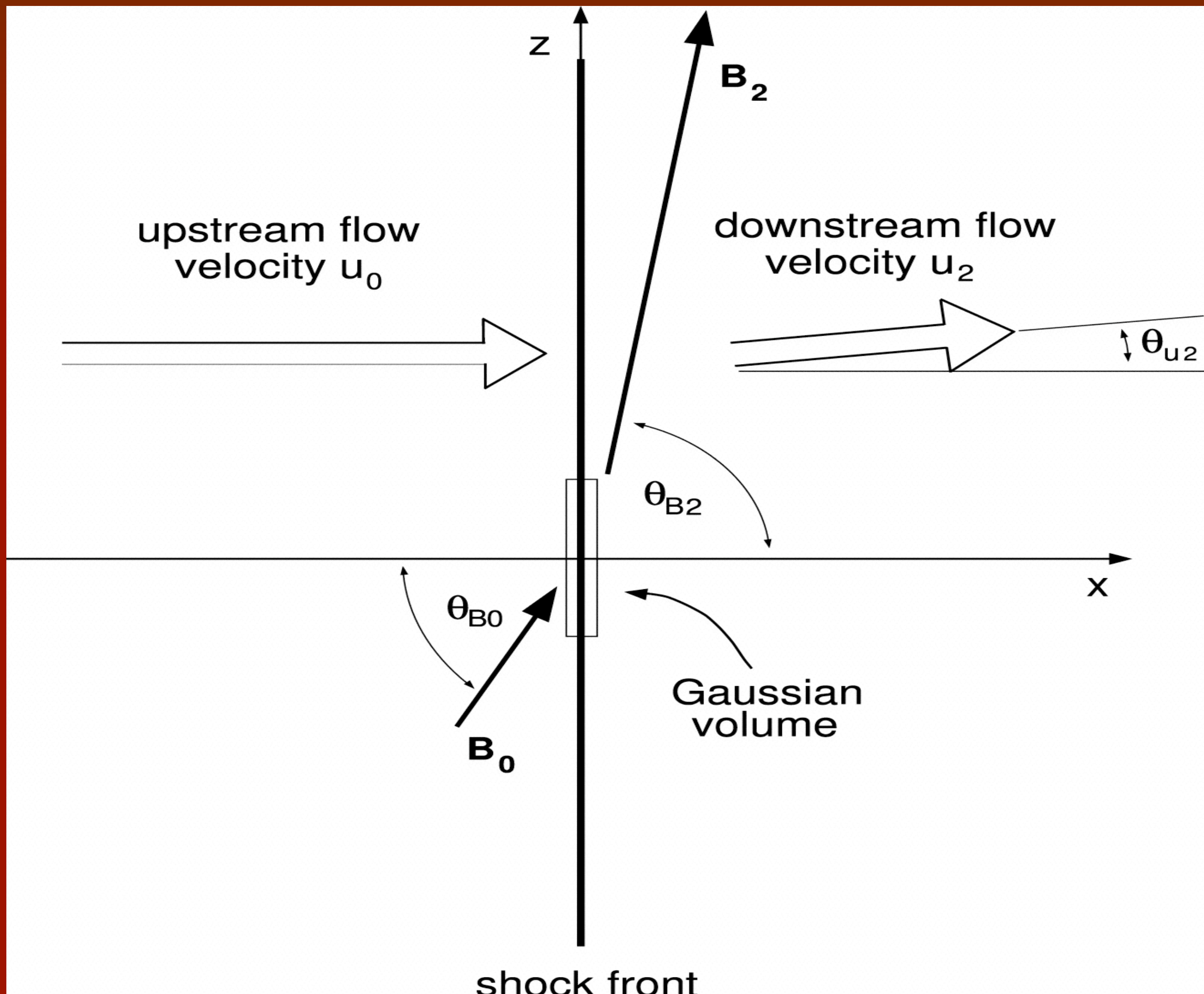
- Monte Carlo results for parallel shocks;
- Spectrum flattens and becomes more structured as u_1->c;
- Relativistic kinematics increases energy gains in shock crossings.

Relativistic Shocks: Spectral Dependence on Scattering

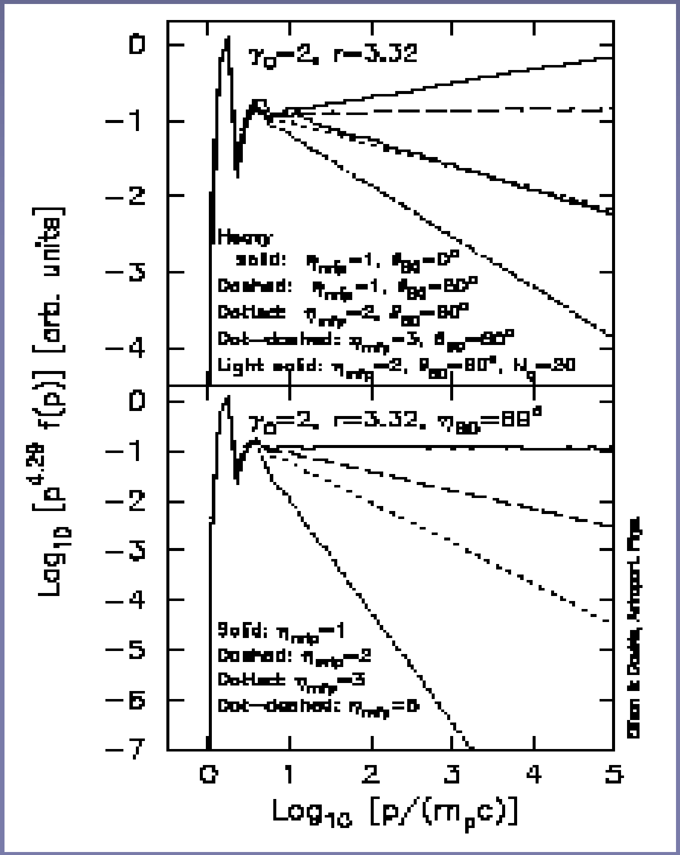
- Deviations from ``canonical'' index of 2.23 (Bednarz & Ostrowski 1998; Kirk et al. 2000; Baring 1999) occur for scattering angles outside Lorentz cone;
- Large angle scattering yields kinematically structured distributions;
- (e.g., Baring 2005)

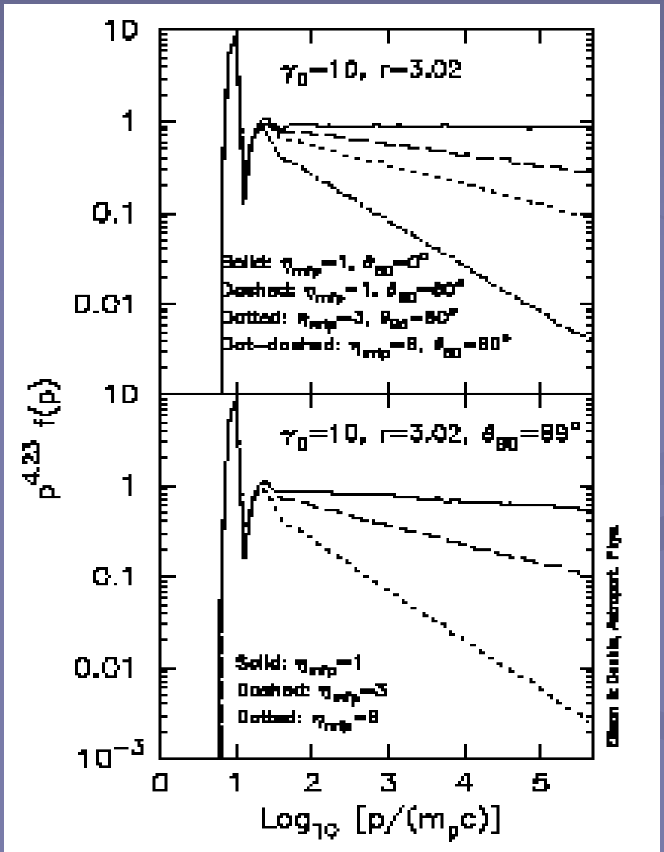


Oblique Shock Geometry



Relativistic Shocks: Spectral Dependence on Field Obliquity and Diffusion



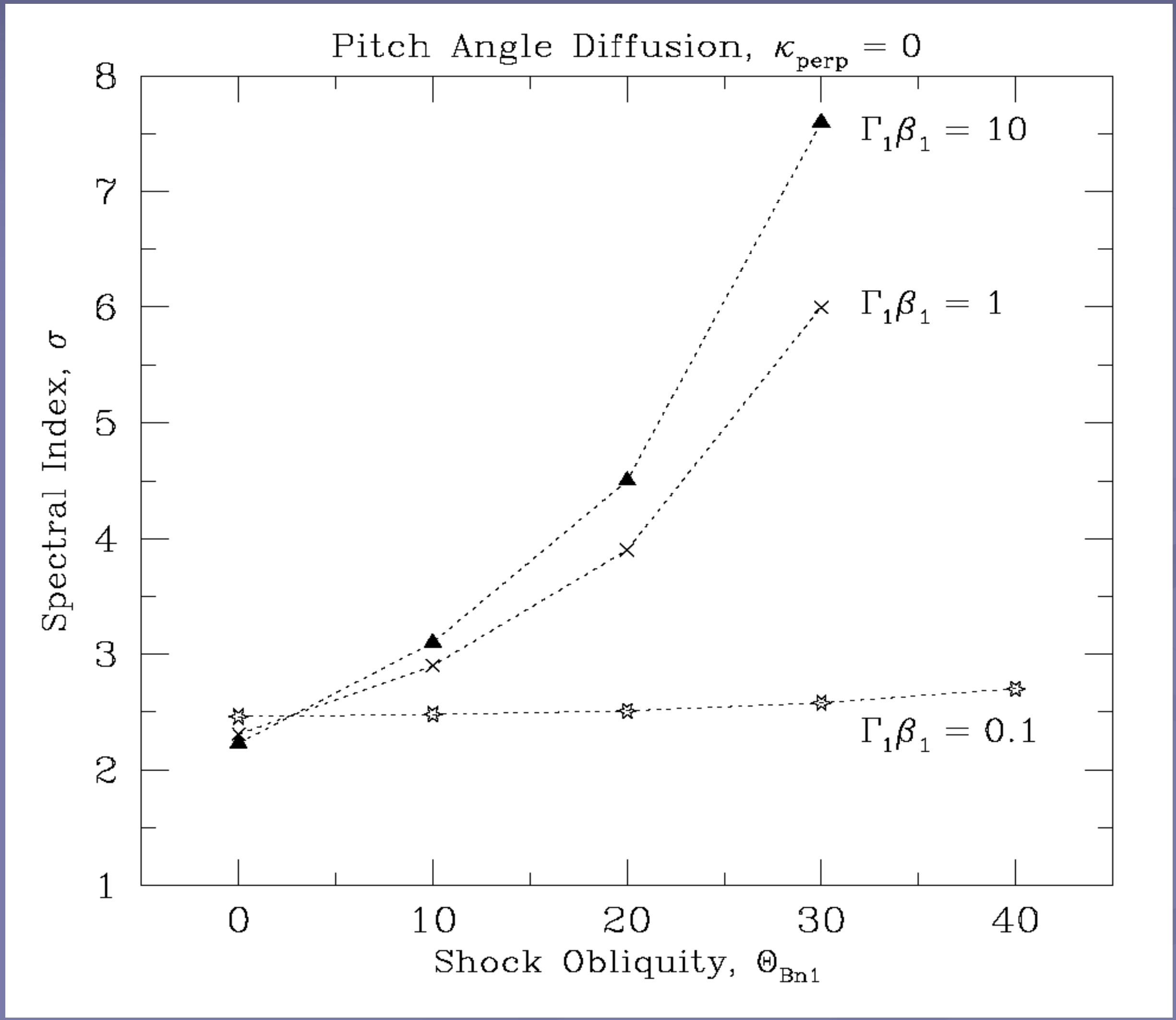


Ellison & Double (2004)

- Increasing upstream B-field obliquity and/or ratio of mean free path to gyroradius steepens the continuum (e.g. Bednarz & Ostrowski 1998; Ellison & Double 2004; see also Kirk & Heavens 1989).

Spectral Index and Shock Obliquity

r=3,
M_S >>1
and
M_A >>1
in all
cases.



<- cosmic sources

Baring (2005)

Implications for UHECRs and Gamma-Ray Bursts

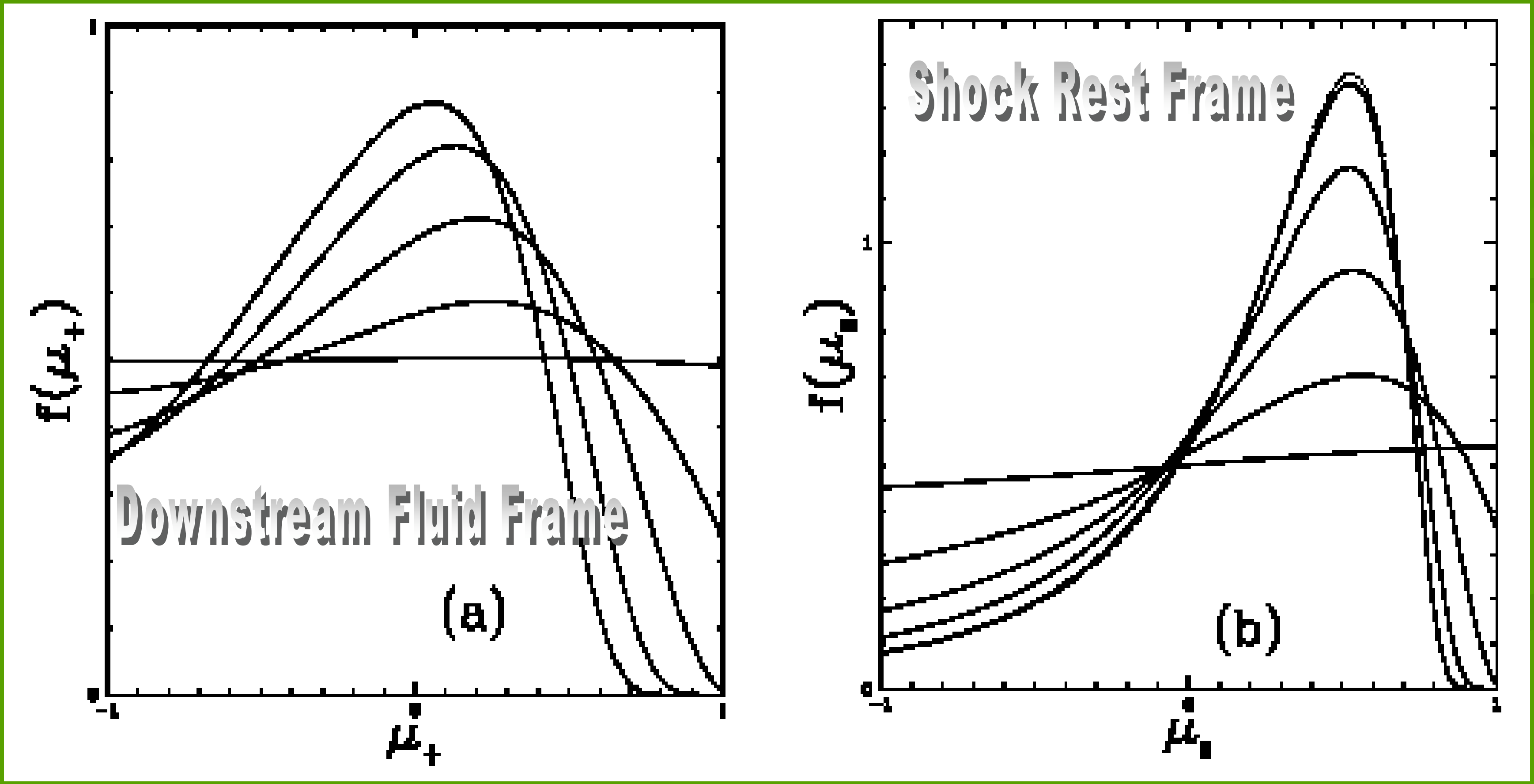
- Relativistic shocks can generate a multitude of spectral forms power-law indices depend on shock parameters and scattering properties;
  - **=> Non-canonical spectral index**
- Spectrum is only flat for quasi-parallel shocks *or* very strong turbulence;
- GRB prompt emission, and UHECR generation (see Milgrom & Usov 1995, Waxman 1995 for GRB/UHECR model) explained by *mildly-relativistic shocks* that are *not quasi-perpendicular* (for diffusive acceleration scenarios).

Character of Relativistic Shocks

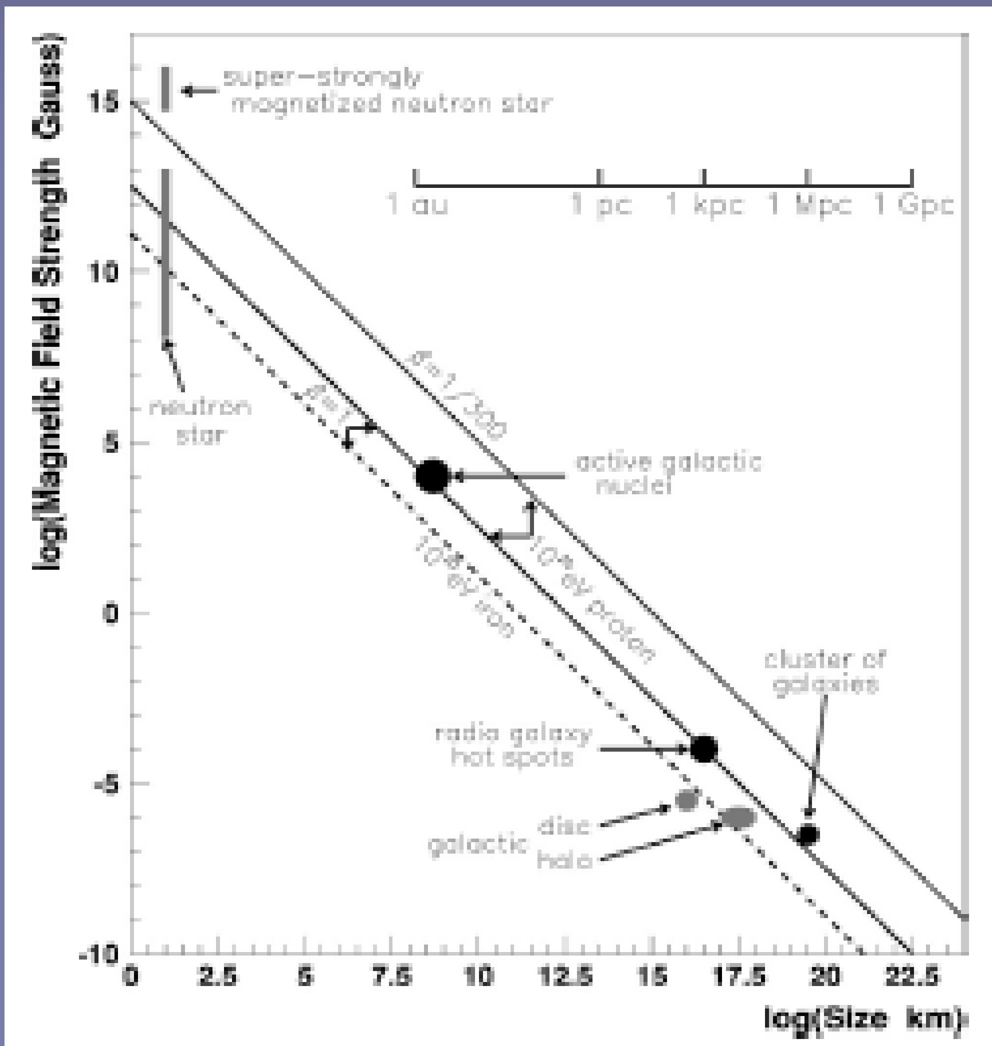
- Character of relativistic shocks defined by their intrinsic anisotropy: convective influence is profound;
- Escape downstream a strong function of shock speed, field obliquity: convective loss rates are high;
- Acceleration times are not modified strongly by relativistic effects.

Anisotropies in Relativistic Shocks: Pitch Angle Diffusion, $0.1c < u_1 < c$

Kirk, Guthmann, Gallant & Achterberg (2000)



Cosmic Ray Acceleration: Fields and Spatial Scales



- Hillas (1984) plot: contours of fixed E_{max} in B-R space;
- Generally, extra-galactic sources needed to produce UHECRs;
- Acceleration timescale is inverse gyrofrequency.

Acceleration Times: What happens for Relativistic Shocks?

Non-relativistic shock rehash:

- For non-relativistic parallel ($\Theta_{\rm Bn1} = 0^\circ$) shocks, in the diffusion approximation (= isotropy), the acceleration time is (e.g. Forman, Jokipii & Owens 1974)

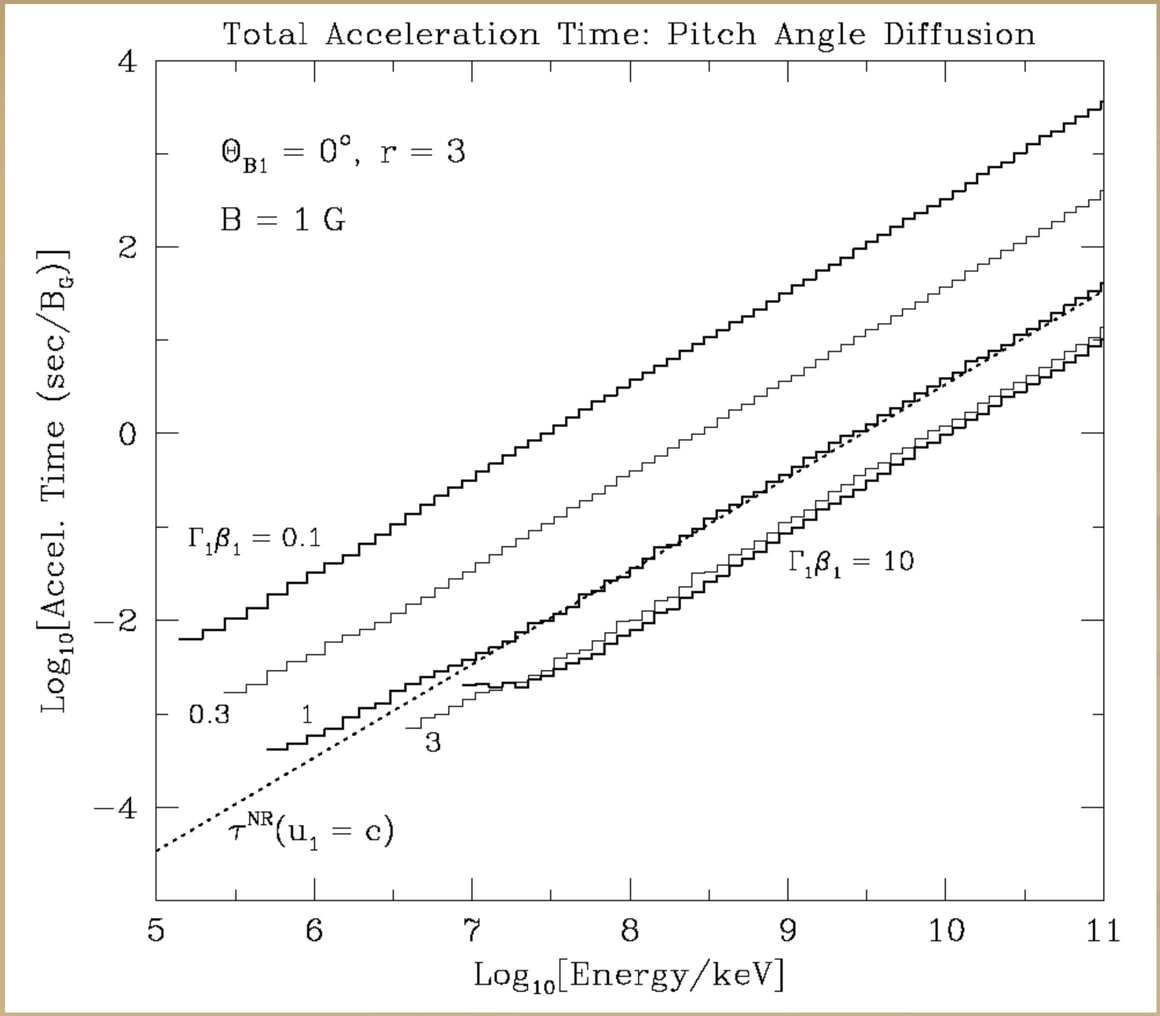
$$\boxed{\tau_{acc}^{NR} = \frac{3}{u_1 - u_2} \int_{p_i}^{p} \left(\frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2} \right) \frac{dp'}{p'} \quad ,}$$

  so that

$$\tau_{acc}^{NR} \approx \frac{0.1}{\beta_1^2} \frac{E_{\rm TeV}}{B_{\rm Gauss}} \text{ sec.}$$

- Hence AGNs can accelerate to UHECRs energies in days if $B \sim 100$ Gauss.
- For GRBs, the variability timescale is much shorter, thereby requiring much higher fields, $B \sim 10^4$ Gauss.

Acceleration Times: Pitch Angle Diffusion



(see Baring 2002)

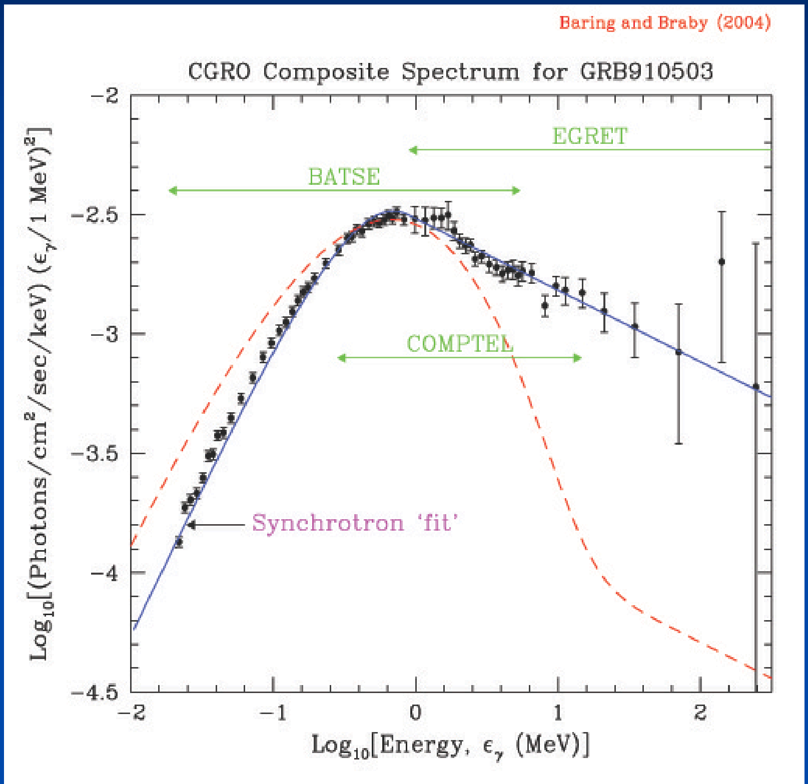
Implications:

- Fundamental acceleration timescale and lengthscale are not changed by special relativistic effects: a particle's proper time is always its proper time,
  - and it couples diffusively to its gyroperiod for gyroresonant processes;
- => UHECRs *require* high **B** fields in sources (e.g. GRBs, magnetars, AGN jets).

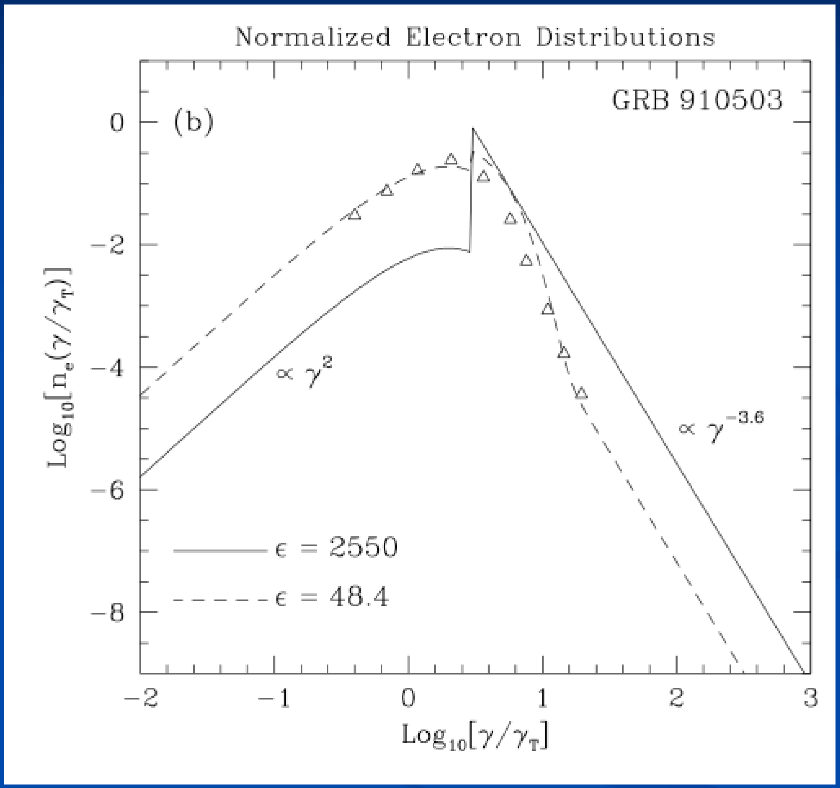
Testing Relativistic Shock Theory

- This is a more difficult game than for their non-relativistic counterparts: fewer systems, and all are remote.
- The bottom line is: *all have to generate the observed photon spectra*.
- Best option: sources with broad-band spectra…gamma-ray bursts.

GRB Prompt Emission Continuum Fitting



Photon spectrum



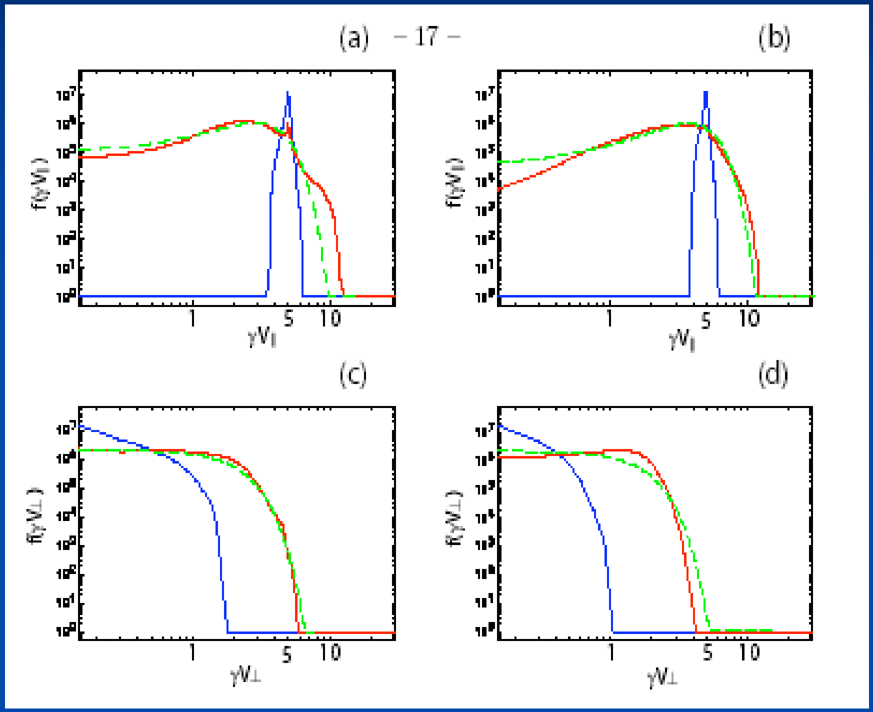
Electron Distribution

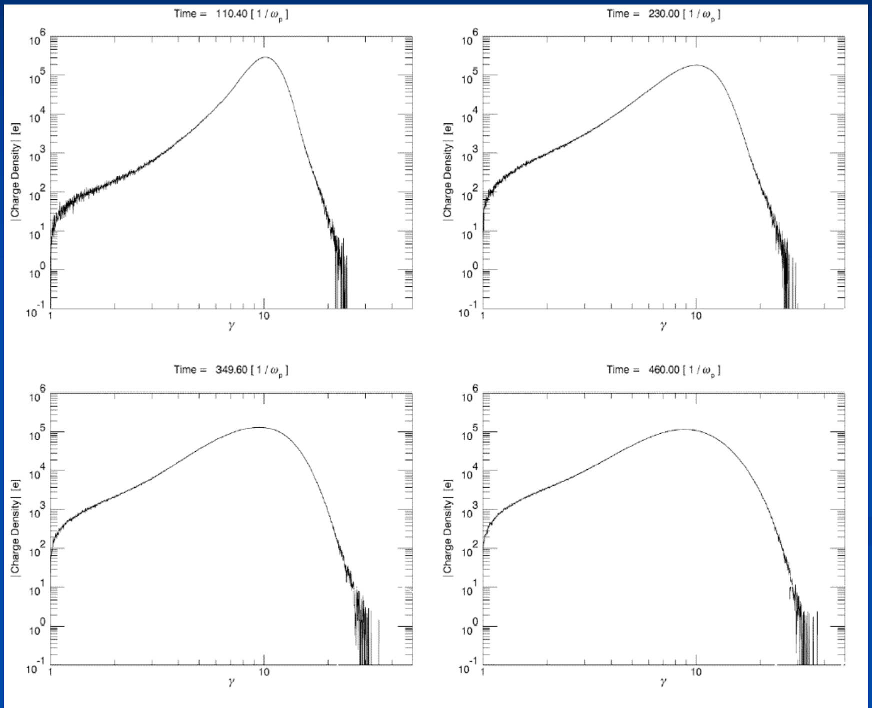
- Synchrotron radiation (preferred paradigm) fits most burst spectra - index below 100 keV is key (Preece et al. 1998 "line of death") issue;
- But, underlying electron distribution is predominantly non-thermal, i.e. unlike a variety of shock acceleration predictions (e.g. PIC codes, hybrid codes, Monte Carlo simulations): see Baring & Braby (2004).

3D PIC Plasma Shock Simulations

Nishikawa et al.

Medvedev





- Nishikawa et al. (ApJ 2006): e-p (left panels) and pair shocks have great difficulty accelerating particles from thermal pool (green is Lorentz-boosted relativistic Maxwellian), dominated by electromagnetic thermal dissipation;
- Medvedev (priv. comm.): Weibel instability simulation with the upper energy cutoff continuously growing in time, i.e. no steady-state;
- *In PIC simulations, non-thermal power-law is at best, not prominent.*

Escape Hatches?

- At face value, GRB spectra indicate that acceleration models need to generate dominant non-thermal e^- distributions;
- But, possible resolutions include:
  - other attractive radiation mechanisms:
    1. small angle synchrotron (Epstein 1973),
    2. jitter radiation (Medvedev 2000, 2006);
- Synchrotron self-absorption acting in concert with upscattering may work (Panaitescu & Meszaros 2000; Liang, Boettcher & Kocevski 2003; discussed in Baring & Braby 2004) - it removes any connection to a thermal population in the BATSE band.

Synopsis, Part II

- Complementary theoretical techniques available;
- X-ray emission in SNRs can sometimes be best modeled using non-linear feedback from energetic cosmic rays in remnants. Goal is to prove the existence of such non-linear hydrodynamic effects in SNRs.
- Evidence of magnetic field enhancement at non-relativistic, SNR shocks is growing: how are high fields generated?
- Acceleration models have difficulty in injecting electrons into the acceleration process in non-relativistic, electron-ion shocks: how is efficient injection driven?

Synopsis, Part II (ctd.)

- Relativistic shocks can generate a variety of power-law indices depend on shock parameters and scattering properties;
- How are electrons accelerated in relativistic shocks? What is their distribution (non-thermal versus thermal)?
- Do gamma-ray burst prompt spectra rule out the operation of shock acceleration, or require more refined interpretation?

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